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Boosting science learning through the design of curriculum materials

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Enhancing science teaching and student learning: A BSCS perspective

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Dr. Bybee has written widely, publishing in both education and psychology. He is co-author of a leading textbook titled Teaching Secondary School Science: Strategies for Developing Scientific Literacy. His most recent book is Achieving Scientific Literacy: From Purposes to Practices, published in 1997. Over the years, he has received awards as a Leader of American Education and an Outstanding Educator in America. In 1998 the National Science Teachers Association (NSTA) presented Dr. Bybee with the NSTA's Distinguished Service to Science Education Award.

Abstract

How can curriculum materials enhance science teaching and student learning? In answering this question I draw upon my experience at the Biological Sciences Curriculum Study (BSCS) to describe the design and development of effective science curricula.

Describing effective curriculum materials requires an understanding of how students learn science. Research in the cognitive and developmental sciences provides a body of knowledge for curriculum developers. Three principles of learning provide the basis for curriculum and instruction in the sciences (Donovan & Bransford, 2005).

1. Students have preconceptions about how the world works.
2. Students' competence in science requires factual knowledge and conceptual understanding.
3. Students can learn to control their own learning through metacognitive strategies.

These findings have clear and direct implications for the design and development of science curricula.

1. Science curriculum and instruction should facilitate conceptual change.
2. Science curriculum and instruction should be based on fundamental concepts and complementary facts.
3. Science curriculum and instruction should provide opportunities for students to learn and develop metacognitive strategies.

Since the late 1980s, BSCS has used a research-based instructional model to organise and sequence developmentally appropriate experiences for students that consist of the following phases: engagement, exploration, explanation, elaboration and evaluation. Known as the BSCS 5E Instructional Model, this model addresses the need for systematic science teaching based on a contemporary understanding of how students learn.

BSCS also has used the *National Science Education Standards* to guide the decisions about the content in curricula developed or revised since the mid-1990s when the standards were released.

Recent studies have indicated that when BSCS programs are used with fidelity, the gains in student learning are great. These results may be attributed to close attention to criteria for learning in the selection of science content and instructional sequence, the use of 'backward design' in developing materials, the extensive support for teachers in the form of teachers' guides, and the complementary professional development of teachers implementing the curriculum.

How can curricula enhance science teaching and student learning? A slightly deeper and more specific question than that is: what is the form and function of effective curriculum materials? These questions will be addressed in the following discussion. After a brief introduction to BSCS (Biological Sciences Curriculum Study), I will first discuss what we know about how students learn science and introduce an instructional model based on this research from the cognitive sciences. I will then review the curriculum development process at BSCS and describe a contemporary high school program and evidence of student learning attributed to that program.

A brief history of BSCS

A committee of the American Institute of Biological Sciences (AIBS) established BSCS in 1958. At its birth, BSCS had a single grand vision – to change the way biology was taught in American high schools. BSCS accomplished this goal by publishing three innovative biology textbooks in 1963. These textbooks became known as the Yellow Version

(Biological Science: An Inquiry into Life), the Blue Version *(Biological Science: Molecules to Man)*, and the Green Version *(Biological Science: An Ecological Approach)*. These textbooks were widely adopted in the United States, and by the mid-1970s, BSCS programs had over 50 per cent of the high school biology market. Further, the international community recognised the quality of these new biology programs and began adapting them for use in their respective countries. One of the enduring examples is the adoption of the BSCS Green Version by Australia. The Australian program is titled 'The Web of Life'. To date, BSCS programs have been translated into 25 languages for use in more than 60 countries.

Though BSCS began with a focus on high school, the organisation quickly expanded beyond high school by developing programs for elementary school, middle school, and college. A 1992 BSCS elementary program *Science for Life and Living* was adopted for Australian schools by Denis Goodrum and his colleagues. In Australia, that program was adapted and implemented as *Primary Investigations*.

BSCS is a 'curriculum study'. Our name indicates that the organisation does not focus on curriculum development in isolation. BSCS also has provided professional development and conducted research and evaluation studies for as long as we have developed instructional materials.

This brief introduction and history of BSCS sets the stage for an important point: BSCS and organisations like it in the United States and other countries such as Australia have developed sophisticated approaches to designing, developing and implementing innovated curriculum materials. The time, effort and expertise of professional curriculum development groups stand as an important innovation from the Sputnik era.

This introduction provides a context for the BSCS perspective on curriculum development and what we do to enhance science teaching and learning. I will describe what goes into contemporary curriculum development at BSCS and use *BSCS Science: An Inquiry Approach*, a new multidisciplinary program for high schools, as an example. Our work begins with an understanding of recent research on learning.

How students learn science

If one is interested in enhancing science teaching and learning, it seems only reasonable to begin with an understanding of how students learn science. Several decades of research in the cognitive and developmental sciences have built a knowledge base that curriculum developers can use. This research has been synthesized by the National Research Council (NRC) and described in several publications, *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, & Cocking, 2000), *Knowing What Students Know* (Pellegrino, Chudowsky, & Glaser, 2001), and *How Students Learn: Science in the Classroom* (Donovan & Bransford, 2005). Three principles of learning from this body of knowledge establish the basis for curriculum and instruction.

1. Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information, or they may learn them for the purposes of a test but revert to their preconceptions outside the classroom.
2. To develop competence in an area of inquiry, students must (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organise knowledge in ways that facilitate retrieval and application.
3. A 'metacognitive' approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them (Donovan & Bransford, 2005, pp. 1–2).

Based on these research findings, curriculum materials should be designed with the knowledge that students' current conceptions may not align with recognised scientific knowledge about how the world works and those current conceptions must be engaged and challenged in order for change to occur. Second, both facts and a sound, conceptual framework are essential. And, third, curriculum and instruction should embed 'metacognitive' strategies.

Finding 1 reminds us that students have preconceptions, misconceptions, and naïve theories, which is to state the obvious. Identifying the means to facilitate conceptual change seems to me to be the essential insight and extension of the research on students' understanding of how the world works – from a scientific perspective. The work of individuals such as Rosalind Driver and her colleagues (1986; 1989), Peter Hewson and his colleagues (1981; 1989), Richard White and Richard Gunstone (1992), Mike Atkin and Robert Karplus (1986), and Bill Kyle and Jim Shymansky (1989) addressed the crucial process of conceptual change and science teaching and set the stage for the design and implementation of instructional models in curriculum programs. At BSCS we had to meet the challenge of translating the findings and insights from the aforementioned individuals to something understandable, usable, and manageable by science teachers. In the late 1980s, we created the BSCS 5E Instructional Model, which I will return to later in the discussion.

Finding 2 reminds us that any discipline is based on a structure of facts and concepts. Although this idea at first seems obvious, what is not so obvious is that textbooks and classroom instruction often disregard the structure of disciplines in the information that is conveyed to students. Not only must these structures be made explicit, but students must also be taught how to retrieve information about the discipline. Like many other educational recommendations, using a curriculum framework for instructional materials has historical connections to Jerome Bruner's (1960) idea of that 'structure of disciplines' should be the basis for science curricula.

Finding #3 tells us that a 'metacognitive' approach to instruction presents an additional element to the design of instructional materials. Michael Martinez (2006) recently elaborated on this aspect of student learning. Going beyond the introductory definition of metacognition as 'thinking about thinking', Martinez proposed the definition 'monitoring and control of thought' and the specific function of meta-memory and meta-comprehension, problem solving, and critical thinking. Martinez suggests three ways of introducing metacognitive strategies in science teaching and curricula. First is an obvious recommendation – students must have experiences that require metacognition. Second, teachers should model metacognitive strategies by 'thinking aloud' problem solving and inquiry-based activities. Finally, students should have opportunities to interact with other students. This suggests the need for group work and an inquiry-oriented approach to the science curriculum.

Using the key findings from *How Students Learn* (Donovan & Bransford, 2005), one can identify factors that are important for science teaching and the design of curriculum materials. I have done this in Table 1, which is based on an original table prepared by several colleagues at BSCS (See, Powell, Short, & Landes, 2002).

Table 1 Design specifications for teaching and curriculum materials

Key findings from How Students Learn	**Implications for science teaching**	**Requirements for curriculum materials**
Students come to educational experiences with preconceptions.	Teachers should recognise preconceptions, engage the learner, facilitate conceptual change, and employ strategies that respond to students' prior knowledge.	Incorporation of information about common preconceptions in the process of conceptual change, and the means by which the curriculum can bring about conceptual change. Inclusion of structured sequences of experiences that will elicit challenge and provide opportunities to change preconceptions.
Students should develop a factual knowledge based on a conceptual framework.	Teachers should have a conceptual understanding of science and the appropriate factual knowledge aligned with the concepts.	Base the curriculum on major concepts of science. Connect facts to the organising concepts. Provide relevant experiences to illustrate the concepts and opportunities to transfer concepts to new situations.
Students can take control of their learning through metacognitive strategies.	Teachers should make goals explicit and provide class time and opportunities to analyse progress toward those goals. Teachers should model metacognitive 'think aloud' strategies.	Make goals explicit in materials. Integrate metacognitive skills development into activities. Use small group activities as part of instructional units.

Implications of the findings from cognitive science suggest the need for systematic instructional strategies. The next section describes an instructional model used in contemporary BSCS.

The BSCS 5E Instructional Model

Since the late 1980s, BSCS has used an instructional model consisting of the following phases: engagement, exploration, explanation, elaboration and evaluation. The instructional emphasis for each phase of the model is described in Table 2.

Table 2 The BSCS 5E Instructional Model

Phase	Summary of emphasis
Engagement	Strategies or activities designed to elicit thoughts or actions by the student that relate directly to the lesson's objective.
Exploration	Experiences where students' current understandings are challenged by activities, discussions and currently held concepts to explain experiences.
Explanation	Presentations of scientific concepts that change students' explanations to align with scientific explanations.
Elaboration	Activities that require the application and use of scientific concepts and vocabulary in new situations.
Evaluation	Culminating activity that provides the student and teacher with an opportunity to assess scientific understanding and intellectual abilities.

Although the BSCS model was created prior to the NRC synthesis of cognitive research, that research provides support for the model. Following is a quotation from *How People Learn* (Bransford, Brown, & Cocking 2000).

> An alternative to simply progressing through a series of exercises that derive from a scope and sequence chart is to expose students to take major features of a subject domain as they arise naturally in problem situations. Activities can be structured so that students are able to explore, explain, extend, and evaluate their progress. (p. 172)

The quotation presents a research-based recommendation that uses terms to describe an instructional sequence that very closely parallels the BSCS 5E Instructional Model. The BSCS model provides experiences and time for students to recognise the inadequacy of their current ideas, to explore new ways of explaining the world, to reflect on their thinking, and to construct new conceptions of the natural world.

In 2006, the NRC published *America's Lab Report: Investigations in High School Science*. This report further supports the use of instructional models such as that used by BSCS. In the analysis of laboratory experiences, the committee also applied results from cognitive research. Researchers have investigated the sequencing of science instruction, including the placement and role of laboratory experiences, as these sequences enhance student learning. The NRC committee proposed the phrase 'integrated instructional units'.

> Integrated instructional units interweave laboratory experiences with other types of science learning activities, including lectures, reading, and discussion. Students are engaged in forming research questions, designing and executing experiments, gathering and analyzing data, and constructing arguments and conclusions as they carry out investigations. Diagnostic, formative assessments are embedded into the instructional sequence and can be used to gauge the students' developing understanding and to promote their self-reflection on their thinking. (p. 82)

The BSCS 5E Instructional Model meets the criteria for integrated instructional units described above. Note also the inclusion embedded assessments and the connection of those experiences to students' self-reflection, or metacognition. This recommendation aligns explicitly with the evaluation phase of the BSCS model. However, each phase of the instructional model provides an opportunity for embedded assessment. Each phase allows teachers and students to assess different aspects of the students' growing understanding of science and abilities of scientific inquiry.

Designing and developing curriculum materials at BSCS

Since the mid-1980s, curriculum development at BSCS has been initiated with a design study. These studies take about a year to conduct and involve a current review of science education at the grade level or levels under study; national and state priorities; careful consideration of curricular elements such as content, instructional strategies, use of laboratory investigations, tests and assessment exercises; and issues of implementation and professional development. The BSCS design studies result in a detailed curriculum framework, specifications for a new program, and a proposal to develop the curriculum. Table 3 lists recent design studies and the resulting core curriculum materials.

BSCS design studies have helped identify what to include in the program; for example, student materials, teacher editions, and implementation guides. Further, the design studies have clarified the goals and constraints as best we could prior to initial development. One of the important and enduring outcomes of this work has been the BSCS 5E Instructional Model.

Since the mid-1990s, BSCS has used the *National Science Education Standards* (NRC, 1996) as the basis for several aspects of curricular design; for example, content and professional development.

Table 3 BSCS design studies and the resulting core programs

New Designs for Elementary School Science and Health (BSCS, IBM, 1989)
Science for Life and Living: Integrating Science, Technology, and Health (1992)
BSCS Science T.R.A.C.S. (1999)
BSCS Tracks: Connecting Science and Literacy (2006)

New Designs for Middle School Science (BSCS, IBM, 1990)
Middle School Science & Technology (1994, 1999)

Developing Biological Literacy (BSCS, 1993)
BSCS Biology: A Human Approach (1997, 2003, 2006)
Biological Perspectives (1999, 2006)

Making Sense of Integrated Science: A Guide for High Schools (BSCS, 2000)
BSCS Science: An Inquiry Approach (9–11) (2006)
BSCS Science: An Inquiry Approach (6–8) (proposed)

A Design Study for a Capstone Biology Course (BSCS, 2006)

Beginning in the late 1990s, BSCS incorporated the backward design process described by Grant Wiggins and Jay McTighe in *Understanding by Design* (2005). In this process, we begin with a clear statement about what we want students to learn (an enduring understanding based on the content standards). Next, we determine what will serve as acceptable evidence of student attainment of that targeted understanding. Then, we decide what learning experiences would most effectively develop students' knowledge and understanding of the targeted content.

The BSCS 5E Instructional Model provides a concrete example of this process. After identifying the enduring understanding and stating the content outcomes, we go to the 'evaluate' phase and design an activity that would assess students' knowledge and understanding of the content. After clarifying the desired outcomes and means to assess for those outcomes, we design and develop experiences that will provide students with the opportunities to learn the content. This process is interactive as it may result in further refinement of the evaluation activity and activities in other phases of the instructional model. Table 4 summarises this process.

A contemporary example

This discussion centers on an example, *BSCS Science: An Inquiry Approach*. This program is based on the design study, *Making Sense of Integrated Science* (BSCS, 2000) and is currently under development (funded by the National Science Foundation in 2000). The program has been conceptualised as a standards-based science program for grades 9 to 11. We explicitly used the *National Science Education Standards* (NRC, 1996) as the conceptual basis for designing and developing this program (see Table 5). Each year of the program begins with a two-week 'Science as Inquiry' unit and is followed by three core units (eight weeks each): Life Science, Earth–Space Science, and Physical Science. In each of these core units, the first several chapters are devoted to helping students build conceptual understanding of the core concepts. The last chapter helps the students understand how these core concepts play a part in problems and events in the integrated setting of the natural world. The final unit uses problems and projects that are relevant to the lives of high school students to develop an integration of ideas across the sciences.

The design of the program units and lessons builds a conceptual foundation and introduces factual knowledge through the use of meaningful activities that are structured by the BSCS 5E Instructional Model. Table 5 displays the conceptual framework.

The use of a conceptual framework and an instructional model accommodates the research on learning discussed in earlier sections (Bransford, Brown, & Cocking, 2000; Donovan & Bransford, 2005).

Table 4 The Backward Design Process and the BSCS 5E Model

IDENTIFY DESIRED RESULTS
National Standards

DETERMINE ACCEPTABLE EVIDENCE OF LEARNING
DESIGN EVALUATE ACTIVITIES

DEVELOP LEARNING EXPERIENCES AND ACTIVITIES
ENGAGE, EXPLORE, EXPLAIN, ELABORATE

Table 5 BSCS Science: An Inquiry Approach Framework for Grades 9–11

Units	Major concepts addressed at each grade level		
	9	10	11
Science as Inquiry	Abilities necessary to do, and understandings about, scientific inquiry with a focus on: • Questions and concepts that guide scientific investigations	• Design of scientific investigations • Communicating scientific results	• Evidence as the basis for explanations and models • Alternative explanations and models
Physical Science	• Structure and properties of matter • Structure of atoms • Integrating chapter	• Motions and forces • Chemical reactions • Integrating chapter	• Interactions of energy and matter • Conservation of energy and increase in disorder • Integrating chapter
Life Science	• The cell • Behavior of organisms • Integrating chapter	• Biological evolution • Molecular basis of heredity • Integrating chapter	• Matter, energy, and organization in living systems • Interdependence of organisms • Integrating chapter
Earth–Space Science	• Origin and evolution of the universe • Origin and evolution of the Earth system • Integrating chapter	• Geochemical cycles • Integrating chapter	• Energy in the Earth system • Integrating chapter
Science in a Personal and Social Perspective, Science and Technology	• Personal and community health • Natural and human-induced hazards • Abilities of technological design	• Population growth • Natural resources • Environmental quality	• Science and technology in local, national, and global challenges • Understandings about science and technology
	The following standards are addressed throughout grade levels and units: Science as a human endeavor	Nature of science	History of science

Evidence of student learning

A national field test of BSCS Science: An Inquiry Approach was conducted from January to June 2002. The field test comprised urban, suburban, and rural classrooms across 10 states, 31 teachers, 64 classes, and nearly 1600 students. Among the findings, several stand out with respect to the quality and effectiveness of the instructional materials and student achievement.

First, overall results from pre- and post-tests were tracked per student in a total of 1550 paired results. For all pre-post tests, the results demonstrated strong and statistically significant gains in student achievement. Average student gains at both 9th and 10th grade levels were between 20 and 25 per cent.

Second, for both grade levels, classes characterised as having students with ‘general ability,’ ‘high ability’, and classes where these abilities were ‘mixed’, each demonstrated a significant increase from pre-test to post-test, independent of ability level of students (See Figures 1 and 2) (Coulson, 2002).

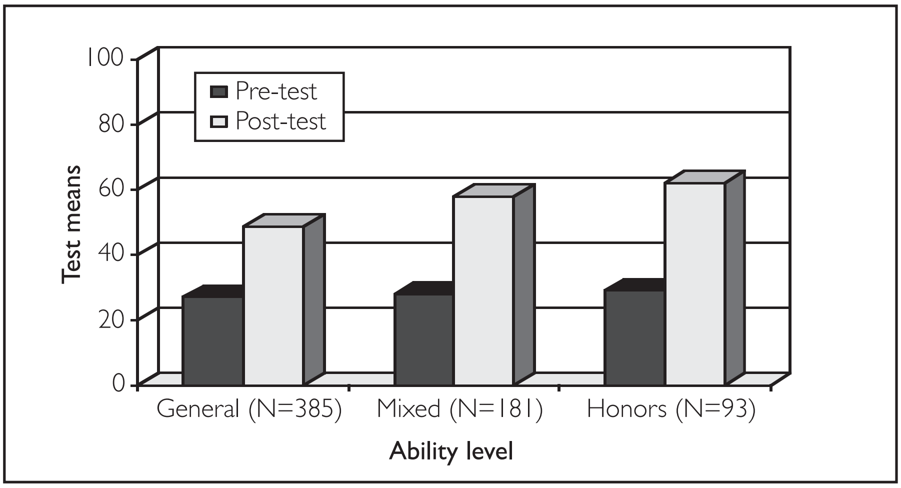

Figure 1 9th grade test score means by ability level

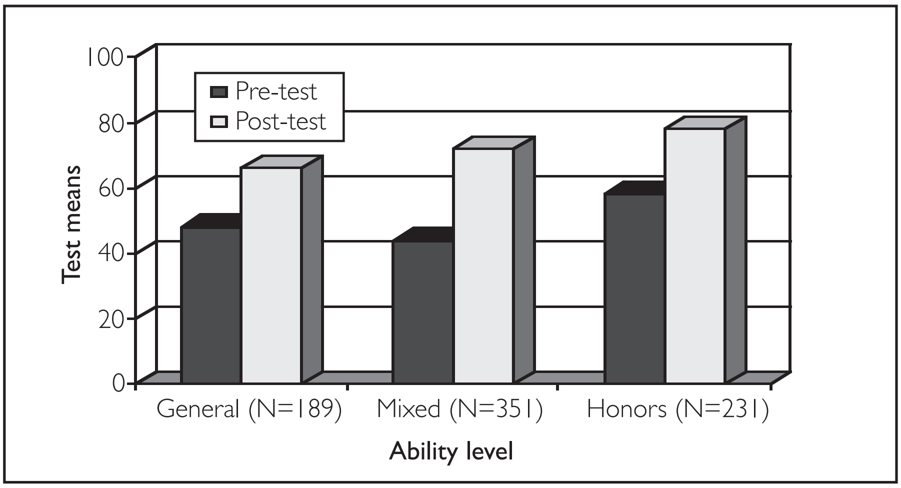

Figure 2 10th grade test score means by ability level

As part of a classroom-based study, student achievement was correlated with level of fidelity of teacher implementation. Based on classroom observations by BSCS staff, the external evaluator used an observation protocol with high inter-rater reliability to assess the degree of fidelity. Teachers demonstrating high fidelity of use of the instructional materials were considered 'high implementers'. Teachers who were teaching the materials with somewhat less fidelity or significantly less fidelity were considered 'medium' or 'low' implementers, respectively. After teachers were assigned to an implementation category, their student test scores were correlated with the teacher's level of implementation.

The results indicate that both 9th and 10th grade students learned more from teachers who taught the materials with medium and high fidelity than from teachers who taught the materials with significantly less fidelity (Coulson, 2002). It is encouraging, however, that students still learned from the materials even when they were in classrooms with teachers identified as low implementers. This finding points to the quality of our student materials as well as importance of our in-depth materials for teachers.

The *BSCS Science: An Inquiry Approach* phase two field-test of the 10th grade curriculum was carried out in 8 states, with 10 teachers and their students. The field-test results yielded strong, significant gains ($p<.001$) on all items in all chapter tests. When items were combined to create a composite score for the chapter, the gains remained significant. In addition, when scores were disaggregated by gender and socioeconomic status (students receiving free or reduced lunch verse those not receiving free or reduced lunch); there was no significant difference between groups (See Figures 3, 4 and 5) (Stuhlstaz, 2006).

Similar results were noted during the phase one of the field test, where statistically significant gains were noted across both 9th and 10th grade paired pre- and post-test results from over 1500 students.

How teachers learn

So far my focus has been on the design and development of curriculum materials. It is the case that the optimisation of contemporary curriculum materials requires new and different approaches to teaching. Although the idea was not entirely new (Bruner, 1960), Deborah Ball and David Cohen (1996) made and elaborated connections between teacher learning and curriculum materials, especially for reform-oriented programs.
The requirements for effective implementation of new programs requires more than an introductory workshop. Teachers must understand the science content of the curriculum, understand the importance of the instructional sequences, make use of different teaching strategies, as well as appreciate the subtleties of responding to students' preconceptions in order to facilitate conceptual change.

There is a need to complement professional development experiences and teacher learning through carefully designed curriculum materials. Promoting teacher learning through instructional materials has been referred to as educative curriculum materials (Schneider & Krajcik, 2002; Davis & Krajcik, 2005). Beyond the components designed for students, curricular materials can be designed so they contribute to science teachers' development of science subject matter, knowledge and use of instructional models and strategies, and pedagogical content knowledge of science topics and inquiry.

It would be an overstatement to indicate that BSCS has achieved all it could in the design and development of science curriculum. I do believe, however, it is accurate to indicate we have continually evolved in directions that optimise curriculum materials for teachers' effective use.

Conclusion

I began with the question – How can curriculum materials enhance science teaching and student learning? Based on a contemporary understanding of how students learn science, I used the processes of design and development of curriculum materials at BSCS to answer the question. That answer can be summarised in the following way. First, pay close attention to the criteria for student learning and the appropriate translation of those requirements to curriculum materials. Second, use an instructional model that provides opportunities and time for conceptual change and development of cognitive abilities. Third, use 'backward design' for the process of designing and developing the scope and sequence of the curriculum. Finally, incorporate a means to enhance teachers' knowledge base, including subject matter, pedagogical content knowledge, and teaching strategies.

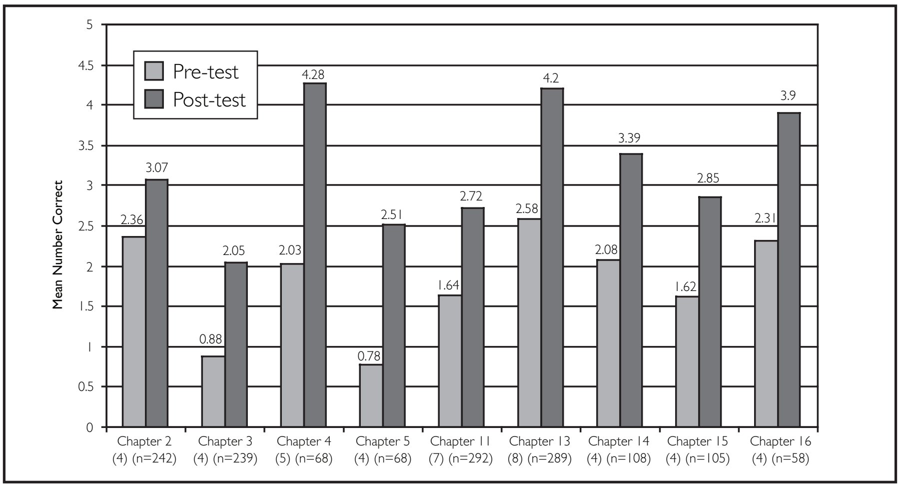

Figure 3

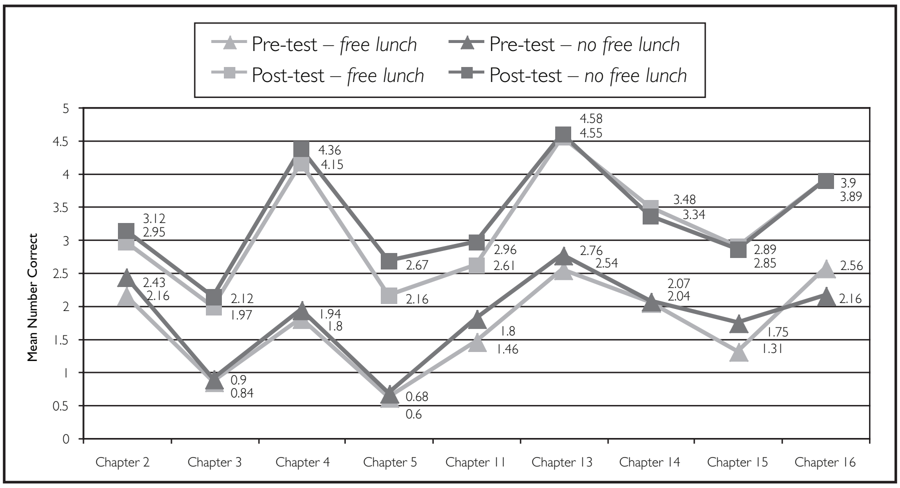

Figure 4

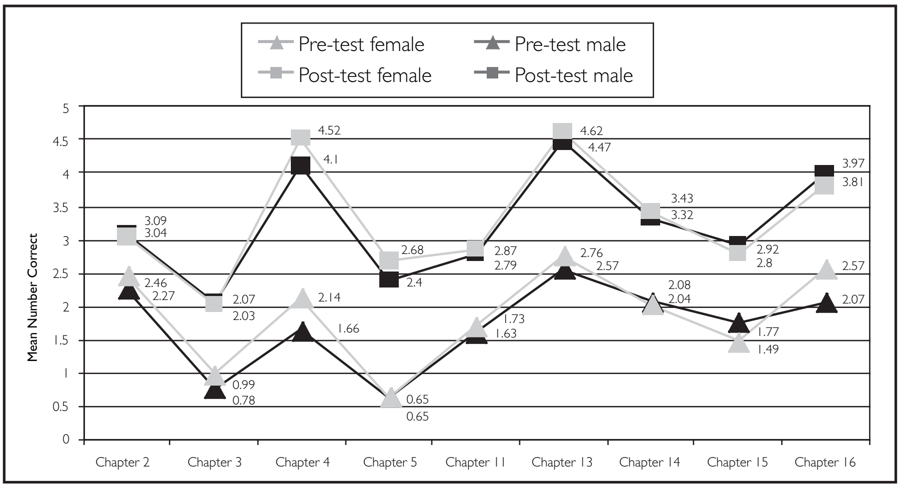

Figure 5

The complementarity of enhancing science teaching and student learning can be achieved through the design, development, and implementation of curriculum materials. Our work at BSCS provides a positive example of what it takes to make the potential of this statement a reality for teachers and students. I believe the BSCS experience can be generalised and applied by other curriculum development groups.

In the end, we want to provide curriculum materials that enhance science teaching and student learning.

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